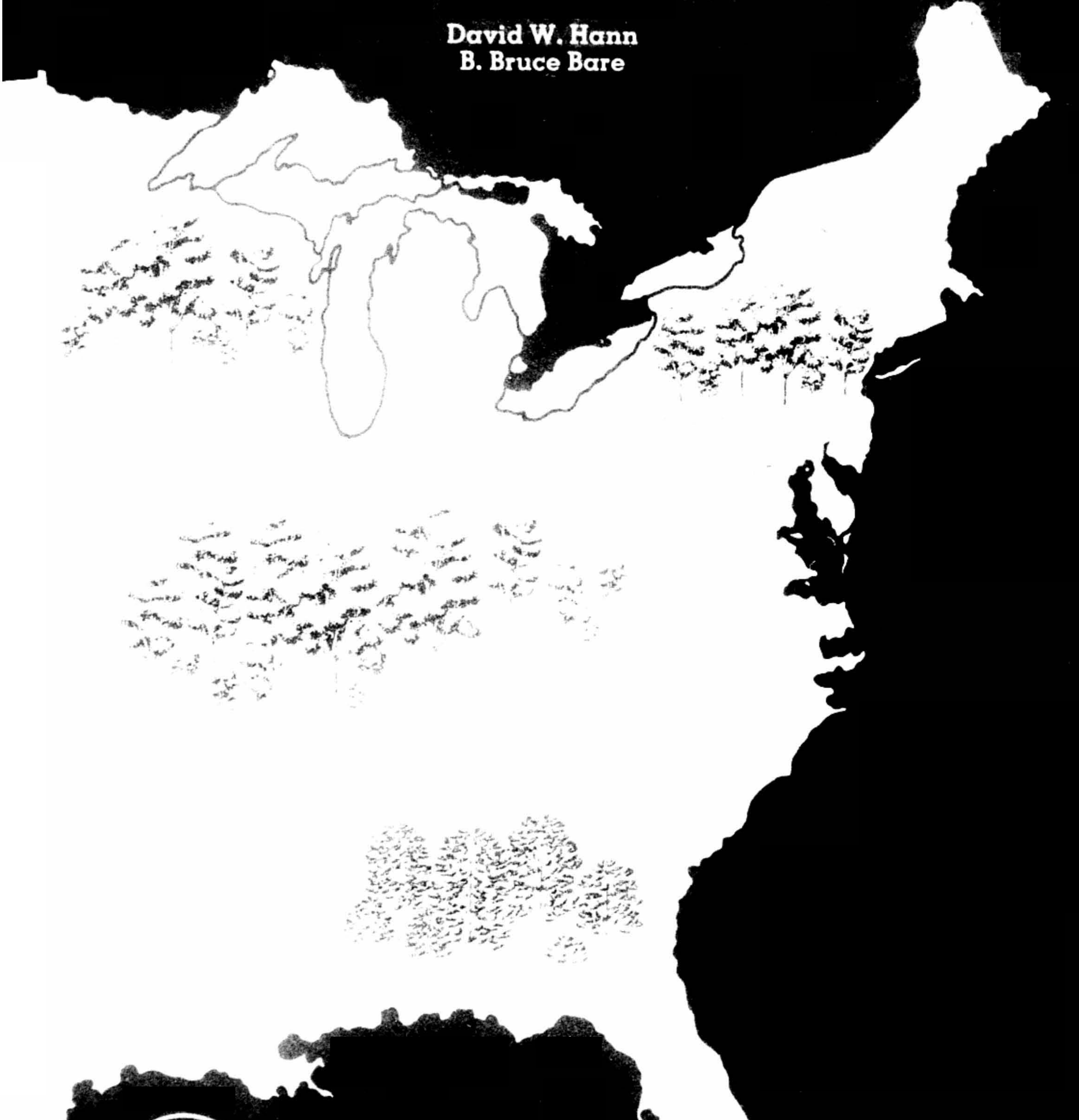
1979

# Uneven-Aged Forest Management: State of the Art (or Science?)

# UNEVEN-AGED FOREST MANAGEMENT: State of the Art (or Science?)

David W. Hann
B. Bruce Bare



General Technical Report INT-50
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service • U.S. Department of Agriculture
Ogden, Utah 84401

USDA Forest Service
General Technical Report INT-50
April 1979

# UNEVEN-AGED FOREST MANAGEMENT: State of the Art (or Science?)

David W. Hann
and
B. Bruce Bare

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

a

## THE AUTHORS

DAVID W. HANN is Assistant Professor in the Department of Forest Management, School of Forestry, at Oregon State University, Corvallis, Oregon. From 1971 through 1978 he was a Research Forester working on problems of inventory techniques for the Renewable Resources Evaluation research work unit in Ogden, Utah. He holds a B.S. in forest management (1968) and an M.S. in forest mensuration (1970) from Oregon State University, and a Ph.D. in forest mensuration (1978) from the University of Washington, Seattle.

B. BRUCE BARE is Associate Professor of Forest Management and Operations Research, College of Forest Resources, University of Washington, Seattle, Washington. He holds B.S.F. (1964) and Ph.D. (1969) degrees from Purdue University and an M.S. (1965) from the University of Minnesota. For the past 8 years, his work has involved the application of quantitative methods to wildland use planning, timber harvesting and forest operations scheduling, and taxation problems.

b

# RESEARCH SUMMARY

Examines some important historical factors that have caused widespread preference of the even-aged management system over the uneven-aged. Major decisions facing forest managers interested in applying uneven-aged management are defined and a review is made of techniques traditionally used, or recently proposed, for use in making these decisions. Finally, problem areas needing further research and development are identified.



# CONTENTS

# THE ROLE OF MANAGEMENT AND SILVICULTURE

Over the centuries, two often conflicting forest management systems--even- and uneven-aged management--have been applied to forests throughout the world. Historically, both systems are rooted in the principles of silviculture, but have been expanded to include forest management objectives and the organization of the forest property. Today, we recognize silviculture and management as separate but related disciplines. Silviculture concentrates on the establishment, tending, and harvesting of forest stands and management focuses on decisionmaking, organization, administration, planning, and control of operations on a forest property to best achieve specified objectives.

Silvicultural systems are classified either as even- or uneven-aged depending primarily upon the type of harvest-regeneration method employed. Stands containing trees of about the same age that develop under full-light conditions without significant border competition are silviculturally classified as even-aged (Davis 1966). Stands containing trees of several ages that develop with significant interaction with surrounding trees of different ages are classified as uneven-aged.

From this ecological-silvicultural basis, the forest manager must decide whether the individual stand is large enough to be recognized and managed as a separate treatment unit. A treatment unit composed of a single even-aged stand is usually managed under the even-aged system of management, and a unit composed of a pure all-aged stand is managed under the uneven-aged system. Stands that are too small to be recognized as separate treatment units are managed under the uneven-aged management system. Such a treatment unit might be composed of several small even-aged stands or clumps--each too small to be treated separately. Thus, the choice between even- and uneven-aged management systems is dictated by silvicultural as well as economic and operational considerations. From a regulatory perspective, control variables of the two systems also differ. The major regulatory control variable in even-aged management is stand age (size) whereas the major control variables in uneven-aged management are stand structure and stocking.

The remainder of this paper focuses on the major decisions facing forest managers who have adopted the uneven-aged system of management. We assume throughout this report that uneven-aged silviculture is a feasible alternative where its use is implied. Lastly, in the discussion that follows, the terms "treatment unit" and "stand" are used interchangeably. A stand is viewed as the smallest sized unit that can be efficiently managed.

# EARLY HISTORY OF THE PROBLEM

The philosophy of even-aged management, developed in Germany and Austria, is based on the conviction that forest management is primarily a science for which mensurational and financial formulas can be developed and used in a systematic manner. The concepts of the fully regulated or normal forest and the doctrine of soil rent are outstanding examples of this form of thinking. Other examples include the myriad of methods for determining rotation length and allowable harvest levels--two of the major decision points in even-aged timber regulation. Interfacing this philosophy with even-aged silvicultural practices is natural because even-aged silviculture is an easily understood system compatible with the concept that forest management can be systematized (Davis 1966; Knuchel 1953; Meyer and others 1961).



The philosophy of uneven-aged management was developed mainly in France and Switzerland after the advancement of the even-aged philosophy. It was based on the concept that forest management is primarily an art that relies heavily upon the continuous input of the forester's ecological experience (with its scientific base) and silvicultural judgment in order to implement the management plan and to meet the stated objectives. This philosophy is compatible with the uneven-aged silvicultural system of selection harvesting where strong emphasis is also placed on the forester's experience and judgment (Davis 1966; Knuchel 1953; Meyer and others 1961).

A review of contemporary forest management literature reveals that uneven-aged management is still treated more as an art than a science (U.S. Department of Agriculture 1975, 1976). Additionally, the distinction between uneven-aged silviculture and management is often so blurred that many students of forest science have come to believe that uneven-aged management and silviculture are inseparable. In this paper, we show that the science of uneven-aged management is readily distinguishable from uneven-aged silviculture and that uneven-aged management is just as amenable to systematic treatment as is even-aged management.

Aside from obvious silvicultural and regulatory differences, the two management philosophies can be differentiated by what forest managers perceive to be the objectives of forest management, the relative weight assigned to each objective, and the methods used to achieve them. Knuchel (1953, p. 12), a Swiss forester who favored uneven-aged management, defined the objectives of forest management as follows:

1. Maintenance of the health and resistance to damage of the forest; raising the productive capacity of the soil and of the stands to the highest volume possible on the site and maintaining that productive capacity.

2. Continuous production of the highest possible volume of valuable timber.

3. Promoting the protective effect of the forest in the widest sense (protection against soil erosion, avalanches and flooding, protection of the scenery, protection of the native flora and fauna).

4. Provision of regular employment for the local inhabitants, especially during the time when labor is not wanted for agriculture.

5. Providing the highest possible financial yield.

6. The forest should work in a sense like a savings bank, in that in time of need it is in a position to supply a greater yield of material than in normal times, without losing its productive capacity.

While these objectives could also be met by even-aged management, many proponents of the uneven-aged philosophy believe that even-aged management fails to meet objectives 1, 2, 3, and 6. They believe that even-aged management results in the development of a monoculture favoring a few species (primarily conifers) raised in single species age-homogeneous stands that are more susceptible to various damaging agents. They also contend that even-aged management has resulted in the conversion of "natural site" species to "introduced" species often with disastrous effects; the cutting of immature trees instead of producing the "...highest possible volume of valuable timber"; greater disturbance of the site with resultant impacts upon soil productivity, soil stability, scenic amenities, and native flora and fauna; and management plans that are disrupted when actual cutting deviates significantly from the scheduled cut.

The philosophy of uneven-aged management emphasizes protection and improvement of a stable forest environment, the guarantee of forest sustention and production of large-sized, high-quality timber. Its proponents believe that these objectives should not be sacrificed for higher rates of return on forest capital, greater wood fiber, and (or) management simplicity.

Forest management in the United States today generally follows the even-aged philosophy. Reasons are varied but can be attributed primarily to (a) the attractiveness of even-aged management as an effective means of converting a forest composed of decadent or high-graded stands to a regulated forest, (b) the dawning of the age of intensive management in the 1950's with its needs for more efficient means of managerial control, (c) the ease of implementing management prescriptions on the ground, and (d) the historic dearth of uneven-aged management techniques for large forest properties.

# THE PROBLEM TODAY

Recently, the Forest Service set aside a considerable amount of forest land acreage for "use influence," scenic, or backdrop zones to protect scenic amenities among others. A large portion of this land is at low elevations and has good access. The Forest Service action has taken the land out of normal timber production and has put it into a category designated for modified handling. Until recently, these special areas have received little or no treatment. With increasing demands for wood products, it is questionable if this condition will persist. These special areas seem ideal for the application of uneven-aged management principles.

In addition, the National Forest Management Act of 1976 restricts the Forest Service as to where and how even-aged management can be used. Thus, renewed attention has been focused on uneven-aged management as a system that may satisfy Congressional intent. Further, in 1975, the Forest Service evaluated the potential impact of various forms of uneven-aged silviculture during preparation of the Renewable Resources Program pursuant to the Resources Planning Act of 1974.

There is little doubt that these and other factors, such as public pressure, have stimulated renewed interest in uneven-aged management. Recently, the Forest Service conducted an eastern and western in-service workshop on uneven-aged silviculture and management (U.S. Department of Agriculture 1975, 1976; and Alexander and Edminster 1977a). Also, uneven-aged management is being conducted for selected tree species on both Indian and private industrial lands in the West (Steering Committee for Indian Reservation Forests 1977) and is used in the East, South, and Midwest (Davis 1966; Smith 1962; and U.S. Department of Agriculture 1973).

We feel that a forester should have a broad spectrum of management techniques, along with the necessary knowledge and tools to appropriately apply them, in order to best meet management objectives. Thus, it is important that both uneven-aged and even-aged management systems receive adequate attention and development. This is especially important in the case of uneven-aged management because the prevailing wisdom implies that this form of management is more of an art than a science--a time-honored doctrine that we challenge in this paper.

Given renewed interest in uneven-aged management, we believe that a summary of our current state of knowledge is in order. This summary is presented in three parts: (a) an examination of the major decisions facing managers who intend to practice uneven-aged management; (b) a discussion of the methods currently available to assist managers in reaching these decisions; and (c) a statement of future work required to improve and extend our knowledge of uneven-aged management systems.



# MANAGEMENT DECISIONS

Before an examination and evaluation of uneven-aged management tools can be made, the major decisions facing the forest manager interested in applying uneven-aged management must be specified and understood. Careful thought, coupled with a literature review of both European and American literature, suggests that most of these decisions can be reached when the following items have been thoroughly examined and decided upon:

1. *The optimal, sustainable diameter distribution for a given stand, expressed as number of trees in each diameter class.*--Under this definition, determination of optimal diameter distribution also establishes optimal stocking and maximum tree size because of their interrelationships. The form of the optimal diameter distribution, its stocking, and maximum tree size historically have been treated separately. This historical separation was probably the result of the methodology used at that time to derive the desired number of trees in each diameter class. There is nothing to indicate that these decisions must be treated separately. The true question facing the manager is, "How many trees should I maintain in each diameter class in order to meet the stated objectives?"

The criterion of optimality depends upon management objectives and constraints. For example, the objective might be to maximize fiber production, expressed as total stem cubic-foot volume, with the constraint that a minimum number of trees be maintained in specific diameter classes for wildlife protection and esthetic amenities. Other optimization criteria could be to maximize saw log production, present net worth, cash flow, or marginal value growth percent. In addition to management objectives and constraints, it is expected that the optimal diameter distribution will vary depending upon forest species, cutting cycle length, and site quality.

2. *The optimal species mix for a stand.*--Besides its influence upon the form of optimal diameter distribution, species is also important in meeting management objectives. The objectives of maximizing fiber production might favor one species or species mix while another species may be best for maximizing saw log or veneer production, marginal value growth percent, or wildlife habitat requirements.

3. *The optimal cutting cycle length for each stand.*--Again management objectives play a significant role. However, constraints, such as minimizing disturbance to stand and site, physical and economic accessibility, and (or) logging equipment limitations also can influence the optimal cutting cycle length. Also, it should be remembered that cutting cycle length will influence optimal diameter distribution.

4. *The optimal conversion strategy and conversion period length for each stand.*--Given that the optimal diameter distribution for a desired species and cutting cycle length has been established, it is necessary next to determine the optimal cutting strategy for converting existing stands to the optimal sustainable condition. Intimately related to this is the question of optimal length of the conversion period for meeting management objectives.

5. *The optimal scheduling of compartment treatments and the date of entry for each compartment.*--Compartments, delineated by permanent boundaries, are typically defined as the primary unit of management, and are composed of one or more treatment units (hereafter labeled stands). Management decisions 1-4 have dealt with individual stands in each compartment. Ultimately, however, the manager is interested in learning how to schedule treatments in each stand so that his objectives for the forest as a whole will best be met. A possible constraint of management might be to treat all stands in a compartment at the same time. If so, previously determined optimal stand

treatments may have to be modified in order to meet forestwide objectives. When to first enter each compartment for optimal results is also of concern. Other constraints might be to maintain a minimum and (or) maximum wood flow in order to meet and (or) not exceed manufacturing capabilities; to maintain a nondeclining, even flow of wood; to generate a desired cash flow; or to maintain a minimum or maximum staffing level. The solution to this final problem, which incorporates all preceding questions, will provide the "allowable" cut for each planning period that best meets the objectives of management.

## AN EARLY ATTEMPT TO ANSWER QUESTIONS

Matthews (1930) made an early attempt to quantify some of the aspects of uneven-aged management in this country in order to answer questions concerning conversion strategies, length of cutting cycle, "rotation" length (age of oldest tree in the stand), and allowable cut. Lacking better information, he assumed that the uneven-aged stand could be viewed as a composite of small, equal-sized, even-aged components that are well mixed throughout the stand. Therefore, his concept of the "ideal" structure of the uneven-aged stand could be determined by data taken from normal yield tables of even-aged stands. This concept of the structure of uneven-aged stands was later laid to rest by Walker (1956) and Reynolds (1954), Walker concluding that to characterize uneven-aged stands in such a manner was "..misleading, inaccurate, and a waste of time."

## DE LIOCOURT'S CONSTANT "q" VALUE

In another attempt to quantify some of the aspects of uneven-aged management, Meyer (1943, 1952) and Meyer and others (1961) took the work of French forester de Liocourt, expanded upon it, and applied it to forests in Mexico and the United States. What de Liocourt found was that a balanced, or sustainable, diameter distribution was characterized by a constant "q" value, calculated as the ratio of the number of trees in a given diameter class divided by the number of trees in the next larger diameter class, and by the diameter of the largest tree in the stand. This relationship generates a geometric series and, when plotted, forms the well-known reverse-j shaped curve. Meyer demonstrated how knowledge of the balanced diameter distribution, coupled with additional information concerning present stand structure and growth, could be used to develop a conversion strategy and to estimate future yields.

Duerr and Bond (1952) next examined how, after the best "q" value, species, and largest tree size were determined, the economic criterion of marginal value growth percent could be used to determine optimal stocking, in terms of volume per acre. Optimal stocking was defined as the stocking level at which marginal value growth percent equals the alternative percent rate of return.

Hough (1954) used double sampling to collect growth and diameter distribution data. He used these data to determine a targeted "q" value and a maximum tree size based on the objectives of management and the form of the original diameter distribution. Then he compared the balanced diameter distribution to the predicted diameter distribution at the end of the first cutting cycle to determine the number of trees to cut in each diameter class. For each area under control, this process was repeated just prior to scheduled harvesting. Hough theorized that this repetitive technique would cause the targeted "q" value to approach, over time, the ideal "q" for the given species and site.



Leak (1964) extended de Liocourt's concepts to the unbalanced forest by modeling "q" as a function of diameter, instead of a constant. His objectives were to provide a means for classifying and (or) comparing different diameter distributions; "to aid in describing intermediate or short-term structural goals; and to provide a guide in marking operations."

In the latest development of the "q" concept, Moser (1976) describes a process for determining the distribution of a given amount of stand density (as measured by basal area, tree-area ratio, or crown competition factor) across a diameter distribution in which "q" and the maximum and minimum diameters have been specified.

The early attractiveness of de Liocourt's ideas was probably due to the following: the method provided a quantitative basis for determining an "ideal" or "normal" selection forest to use as an objective; it was useful in determining conversion strategies and allowable cuts; and the method was easy to use at a time when most calculations were tediously done by hand. The recent literature would indicate that these features are still valued (Moser 1976; U.S. Dep. Agriculture 1975, 1976; and Alexander and Edminster 1977a, 1977b).

Some of the questions not answered by de Liocourt's methods were: (a) what "q" value and largest tree size combinations were optimal; (b) were the conversion strategies optimal or even desirable; (c) what about species composition, cutting cycle length, date of entry, and conversion period length; and (d) what compartment schedules were best for a given set of objectives?

More fundamentally, is a balanced distribution, such as that described by de Liocourt, necessary for sustention? Might not other diameter distributions be just as sustainable and yet prove to be better able to meet management objectives? These questions were probably on Davis' (1966) mind when he concluded that, "...a good diameter distribution is determined by the biology of the forest and the purposes of management and not by mathematics...." Leak and Filip (1977), in discussing the use of group selection in northern hardwoods, supported that conclusion.

## RECENT WORK

Some of the most important recent work dealing with the questions of uneven-aged management has been that of Adams (1974) and Adams and Ek (1974, 1975). Their work involves the interfacing of a stand simulator with nonlinear mathematical programing to answer questions concerning optimal stand diameter distribution, cutting cycle length, and conversion strategy. Their stand model was a modified version of a previously developed stand simulator (Ek 1974).

This simulator was used to determine the optimal stand structure that would maximize value growth for a fixed basal area stocking level, cutting cycle length, species mix, and site quality while meeting the constraints of sustainability. This process was repeated for various basal area stocking levels and the resulting different diameter distributions were compared by using the marginal value growth percent criterion to determine the final, optimal distribution for a fixed cutting cycle length, species mix, and site quality. Adams (1976) subsequently has shown how this same procedure can be used to determine the optimal diameter distribution based on "value" stocking rather than basal area stocking. Distributions derived in this fashion are "investment-efficient" because they maximize percent net worth for the investment made in the growing stock.

One requirement of this procedure is that the cutting cycle be equal to, or an integer multiple of, the growth period length of the model. In their example, Adams and Ek (1974, 1975) used a cutting cycle equal to the growth period; however, they also showed how to incorporate longer, multiple period cutting cycles into their optimization process.

After establishing the optimal stand diameter distribution, Adams and Ek (1974, 1975) used nonlinear mathematical programing to find the optimal conversion strategy that maximized present net worth of the stand for a fixed conversion cycle length, species mix, and site quality during the transition from existing stand diameter distribution to optimal distribution. Like the cutting cycle length, the conversion cycle length must be an integer multiple of the growth period. It is also possible to apply the same technique for different transition periods in order to determine the optimal conversion period length on a stand basis.

# WHAT'S NEXT

The milestone work of Adams and Ek (1974, 1975) opens the door to a new set of tools for answering uneven-aged management questions and illustrates that uneven-aged management is subject to much more rigorous analysis than many previously thought. Nevertheless, the development of uneven-aged management systems still lags behind that of even-aged management.

While Adams and Ek (1974, 1975) have incorporated conceptually most of the major decision points facing a manager, their entire analysis was directed at single stands. Consequently, they did not consider the scheduling of compartment or stand treatments viewed from a forestwide position. Secondly, their approach did not adequately treat the problem of determining optimal species mix within a given stand. Lastly, some computational problems remain when more complex situations are encountered. In reviewing the work of Adams and Ek (1974, 1975), we believe that five problem areas, some overlapping, need additional work before their (or any other new) tools can be made fully operational. These problem areas are:

1. Improvement of computer and algorithm capabilities.

2. Development of techniques for interfacing stand simulators to nonlinear programing models.

3. Development of uneven-aged growth and yield simulators.

4. Development of techniques for determining optimal species mixes.

5. Development of optimization tools for scheduling compartment treatments on a forestwide basis.



# COMPUTER AND ALGORITHM CAPABILITIES

In applying their techniques, Adams and Ek (1975) found that the solution process fast approached the limits of either the mathematical programing algorithms or the computer when the cutting cycle exceeded three times the growth period length. A similar problem existed when solving for the optimal conversion strategy. In this case, they discovered that transition periods exceeding four times the growth period could not be handled.

They found also that it was sometimes difficult, if not impossible, to find solutions to these nonlinear programing problems. But, as they suggest, there is reason to believe that some of these problems and limitations soon will be overcome either by applying new mathematical programing techniques, such as the optimal control theory or the decomposition theory, and (or) through improved computer capabilities.

# INTERFACING SIMULATORS TO NONLINEAR PROGRAMING

An important requirement of the Adams and Ek (1974, 1975) approach is a stand simulator that explicitly expresses the change in number of trees in a diameter class as a function of the number of trees in the diameter class and as a function of any other applicable independent variables. Ek's (1974) modified stand simulator is the only uneven-aged simulator reported to date that meets this requirement. Although other modeling techniques do not provide the required explicit equations, it is possible to use numerical analysis procedures to provide estimates accurate enough to determine solutions without the explicit functions (Adams 1974). While theoretically possible, further research is needed to test the feasibility of this approach. One potential problem might be the difficulty in combining the nonlinear mathematical program, the program for the numerical analysis procedure, and the growth and yield simulator together on the same computer.

# GROWTH AND YIELD SIMULATORS

Given that the practical problems with interfacing nonlinear programing to a growth and yield simulator can be worked out, one is then faced with a wide choice of simulator types to choose from. Munro (1974) classified simulators into three categories: single tree/distance dependent, single tree/distance independent, and whole stand/distance independent.

Single tree/distance dependent simulators utilize tree coordinates to appraise intertree competition between a given tree and its neighbors. An example of a simulator of this type with the potential for use in uneven-aged stands is the one reported by Ek and Monserud (1974a, 1974b). The theoretical advantage of this type of simulator is that it can provide the greatest amount of information concerning both tree and stand development. However, the single tree/distance dependent simulators published to date have not demonstrated an ability to predict individual tree development accurately, and they do not seem to predict stand attributes any better than the other types of simulators. It is possible that these results will improve as the "state of the art" improves.

There are several disadvantages to using single tree/distance dependent simulators for answering uneven-aged management questions. First, this type of simulator is difficult and expensive to develop because data with individual tree coordinates are not common. The simulators are also more costly to operate because of the tree coordinate data needed to initialize them and because of the large amount of computer time and space needed to run them.

Second, much of the data generated by this type of simulator are not needed to answer uneven-aged management questions. Thus, there is also a real potential for overloading the information system with extraneous data.

Third, the small plots usually generated by single tree/distance dependent simulators may not be large enough to represent the uneven-aged stand accurately. Finally, because of the large amount of computer space and time needed, it is doubtful that a simulator of this type can be interfaced with nonlinear programing.

Some modelers, who have developed single tree/distance dependent simulators, have tried to circumvent the expense and difficulty of requiring tree coordinates when the simulator is initialized by artificially generating tree coordinates. This basically converts the simulator to a distance independent type insofar as later usage is concerned (Munro 1974).

An example of a single tree/distance independent stand simulator that has the potential for adaptation to uneven-aged stands is Stage's (1973) "prognosis model." Stage's approach has several advantages over the distance dependent type. Besides the obvious advantages of not requiring tree coordinates, his approach does not require the complete enumeration of the plots to be "prognosticated." Instead, it is based on samples drawn from throughout the stand. This lessens the amount of data to run the model and makes it possible to apply the model to uneven-aged stands, which are often large in size.

The disadvantages of single tree/distance independent simulators are that their programs are still large and generate a large amount of information not presently needed to answer uneven-aged management questions. Because of their size, the interfacing of the distance independent simulators with nonlinear programing is as doubtful as with the distance dependent type. It is also generally acknowledged that single tree/distance independent simulators are not designed to provide accurate individual tree development information. Also, their advantage over whole stand/distance independent simulators for predicting stand development has not been demonstrated.

Whole stand/distance independent simulators can range from the simple to the complex. Moser's (1972) set of first-order, ordinary differential equations for expressing change in the total number of trees (or in total basal area) of the stand is an example of a simple uneven-aged whole stand simulator. The differential equations were used to express gross growth, mortality, and ingrowth rates for all trees 7 inches or greater in size. In a later version, Moser (1974) divided the stand into six diameter classes (1.6-4.5, 4.6-9.5, 9.6-14.5, 14.6-19.5, 19.6-24.5, and 24.6+inches). This improvement allowed the monitoring of changes in diameter distribution because of different treatments. For each diameter class, differential equations were again used to model gross growth, mortality, and ingrowth, this time expressed as basal area, cubic-foot volume, or number of trees.

Ek's (1974) uneven-aged stand simulator is also fairly simple. He divided the stand into 2-inch diameter classes and then used a technique analogous to stand table projection to move the trees through the diameter classes. The changes in the number of trees in each diameter class due to ingrowth, upgrowth, and mortality were modeled as nonlinear functions.



The whole stand/distance independent type of simulator is easier to develop, cheaper to initialize and run, and takes less computer core than do the single tree varieties. Also, its smaller computer core requirements make it more likely to be interfaced with nonlinear programing. The main disadvantage is that individual tree information is completely lacking and, for the very simple whole stand simulators, stand structure information is sometimes lacking. However, as was mentioned, the lack of individual tree information is not critical at this time for two reasons: (a) the information is not needed to answer most of the uneven-aged management questions, and (b) simulators that produce individual tree information have not demonstrated an ability to do so reliably.

We believe that relatively small uneven-aged, whole stand/distance independent simulators can be developed that will provide more detailed information than do present whole stand simulators about stand structure and about the growth and vigor of tree classes within the stand. The progress of our work tends to confirm this hypothesis. Once our simulator is completed, we hope that a numerical analysis linkage to a nonlinear programing routine can be developed and tested for feasibility.

# SPECIES COMPOSITION

Both Moser's (1972, 1974) and Ek's (1974) whole stand/distance independent simulators were developed from mixed species data. None of the simulators recognized individual species; so the estimated yields represent only the species mix found in their data. Determining an optimum species mix is an important question for forest managers interested in practicing either even- or uneven-aged forest management. Adams and Ek (1975) concluded that the best way to approach the species composition problem was to use a single tree/distance dependent simulator and a growth maximization algorithm. They rejected using whole stand/distance independent simulators because they believed that (a) multispecies whole stand simulators would be almost as complex as single tree types and (b) determining the parameters in the nonlinear, multispecies equations would tax or exceed existing nonlinear regression programs.

We do not agree. Multispecies whole stand simulators undoubtedly will be more complex than single tree simulators, but we do not feel that they will approach the complexity of individual tree/distance dependent simulators. The problem of nonlinear regression limitations can also be avoided through the use of other modeling strategies.

We base these conclusions on our work in developing a whole stand/distance independent simulator for uneven-aged ponderosa pine. In this simulator, ponderosa pine has been divided into two vigor classes, "blackjack pine" and "yellow pine," based on bark color of the tree. Each vigor class is represented by a separate diameter class distribution. As a result, each vigor class has been handled in a manner analogous to the treatment of separate species in a multispecies model. Separate growth and mortality functions have been developed that interrelate both vigor components of the stand. We have not encountered insurmountable problems modeling these two vigor classes, and we do not believe the simulator is overly complex. A similar approach is worth trying for multispecies simulators.

Given that a simulator can be developed for multiple species, the optimization problems are merely logical extensions of Adams' and Ek's work. As an example, the following formulation is used to determine the optimal diameter distribution for two species ($X$ and $Y$) and a specified level of stocking ($L$):

$$\underset{[X_D(t),\ Y_D(t)]}{\text{Max}} \sum_{D=1}^{N+1} V_D \cdot \Delta X_D + \sum_{D=1}^{M+1} U_D \cdot \Delta Y_D$$

subject to:

$$\Delta X_D \geq 0, \quad D = 1, \ldots, N + 1$$

$$\Delta Y_D \geq 0, \quad D = 1, \ldots, M + 1$$

$$\sum_D (f(D) \cdot (X_D(t) + Y_D(t))) = L$$

$$X_D(t) \geq 0, \quad D = 1, \ldots, N$$

$$Y_D(t) \geq 0, \quad D = 1, \ldots, M$$

In this formulation, $V_D$ and $U_D$ are value functions of diameter for species $X$ and $Y$, respectively; $\Delta X_D$ and $\Delta Y_D$ are the changes in the number of trees in the $D$th diameter class after one growth period; $f(D)$ is the function that determines diameter class stocking; and $X_D(t)$ and $Y_D(t)$ are the initial number of trees in the $D$th diameter class. By eliminating all terms involving species $Y$, the exact one-species formulation of Adams and Ek (1974) results.

An unexplored area is the feasibility of linking a multispecies model with a nonlinear programing routine. Although theoretically possible, such a model might encounter computational limitations. Additional research is needed before definite conclusions can be drawn.



# SCHEDULING OF COMPARTMENTS

The preceding discussion of management decisions 1 through 4 shows that foresters only recently have begun to apply modern decisionmaking tools to help solve uneven-aged management problems. Further, a review of the literature indicates that most of this recent work is directed at the individual treatment unit or stand and not at the forest in its entirety. In fact, little attention has been paid in the literature to the scheduling of uneven-aged compartments for treatments. Loucks (1964) observed that linear programing could be used to schedule treatments in uneven-aged forests, and Norman and Curlin (1968) applied linear programing to the management of a Tennessee Valley Authority (TVA) forest organized for uneven-aged management. The Forest Service Timber Resource Allocation Model (Timber RAM) also is capable of handling uneven-aged management options (Navon 1975). Further, we understand that the mathematical programing system, Max-Million (Ware and Clutter 1971), used extensively to schedule harvest operations in the Southern States has been modified by some users to include uneven-aged management options. Thus, it is apparent that linear programing can be used to facilitate scheduling when an uneven-aged management system is used. To clarify this, we will examine the scheduling problem in more detail, pointing out difficulties to be overcome. A simplified linear programing formulation and two alternative formulations are then proposed. Each formulation is to illustrate one way to interface stand-level information, such as might come from the work of Adams and Ek (1974, 1975), with a forestwide optimization model.

Although optimal stand structure, species composition, and conversion strategy may be determined for each stand, it is highly unlikely that these optimal stand solutions will lead directly to an optimal forestwide scheduling solution. Preliminary work indicates that the decision points for each stand that can be determined by scheduling are time of first entry, cutting cycle length, and conversion length. Therefore, the alternative treatment schedules for each uneven-aged stand are a series of yields that are the result of determining optimal stand structure, species composition, and conversion strategy for a selected set of alternative cutting cycles, conversion lengths, and times of first entry.

We assume at the outset that the forest area has been organized into geographically identifiable compartments, with each compartment composed of one or more individual treatment units or stands. We further assume that all stands are to be treated and managed as uneven-aged stands. However, this assumption can be relaxed without major impact on the formulation that follows. The planning horizon (that is, the number of years over which we wish to plan) is split into a series of planning periods, each of constant length, and an equal multiple of the growth period. This latter assumption is necessary if Adams' and Ek's (1974, 1975) stand optimization procedures are to be used to produce stand-level inputs. However, this limitation may be eliminated if a different approach to stand simulation is adopted. As previously noted, the cutting cycle and conversion length are also restricted to even multiples of the growth period.

We also assume that the scheduling of management activities is done at the compartment level and not at the stand level. Later, we alter this assumption by eliminating compartment boundaries and, in essence, treat the whole forest as a single compartment made up of many stands. For treatment activities, it is necessary to recognize individual stands within compartments. We deal with this by aggregating stand information within a compartment, but we preserve the integrity of the compartment for scheduling purposes.

For each stand in a given compartment, a set of management alternatives is generated. As shown in table 1, each management alternative is characterized by its cutting cycle, conversion length, and date of first entry. One of the management alternatives is assumed to represent the optimal cutting cycle, conversion period, and conversion strategy for a given stand provided by a procedure similar to that of Adams and Ek (1974, 1975). However, this condition can be eliminated without affecting the formulation of the scheduling problem. The remaining management alternatives for each stand are clearly not optimal, but are included to facilitate the compartment level optimization. Compartment summaries are obtained by totaling all stand variables (weighted by stand size) over a given planning period.

Table 1.--*Example of management alternative specification format*

| Management alternatives | | 5-year planning period 1 | 2 | 3 | 4 | ... | Net present value |
|---|---|---|---|---|---|---|---|
| Compartment i | | | | | | | Stand 1 |
| 1 | [1]CC = 10<br>[2]DE = 1 | [3]V | | V | | | C |
| 2 | CC = 10<br>DE = 2 | | V | | V | | C |
| 3 | CC = 5<br>DE = 1 | V | V | V | V | | C |
| . | | | | | | | |
| . | | | | | | | |
| . | | | | | | | |
| n | CC = 5<br>DE = 3 | | | V | V | | C |
| | | | | | | | Stand 2 |
| 1 | CC = 10<br>DE = 1 | V | | V | | | C |
| 2 | CC = 10<br>DE = 2 | | V | | V | | C |
| 3 | CC = 5<br>DE = 1 | V | V | V | V | | C |
| . | | | | | | | |
| . | | | | | | | |
| . | | | | | | | |
| n | CC = 5<br>DE = 3 | | | V | V | | C |
| | Summary for compartment i | | | | | | |
| 1 | | V | | V | | | C |
| 2 | | | V | | V | | C |
| 3 | | V | V | V | V | | C |
| . | | | | | | | |
| . | | | | | | | |
| . | | | | | | | |
| n | | | | V | V | | C |

[1]CC = Cutting cycle.
[2]DE = Date of entry.
[3]V = Volume removed at time of harvest.



While the date of first entry is a useful descriptive variable, it is not used as a control variable in the compartment level optimization. However, it must be equal to or evenly divisible by the cutting cycle and conversion period in our formulation.

The manner in which management alternatives are defined for each stand within a compartment can greatly affect the computational feasibility of the approach being developed. For instance, if a common definition of management alternatives is forced upon each stand in a compartment (as in table 1), the total number of alternatives to examine will be equal to $\sum_{i=1}^{c} a$ where $a$ = the number of alternatives per stand and $c$ = the compartments.

However, if each stand in a given compartment adopts a unique definition for its management alternatives, then the total number of alternatives mushrooms to $\sum_{i=1}^{c} a^{s_i}$ and $s_i$ = number of stands in the $i$th compartment.

A compromise solution to this problem is possible if a priority ranking of management alternatives of each stand within a compartment is determined. This would undoubtedly lead to suboptimization, but would be better computationally than the first approach and more feasible than the second.

Based upon one of the above options, we can proceed to formulate the compartment level scheduling problem as a linear program. Although we assume that our objective is to maximize net present value over the planning horizon, other objectives are equally possible. In so doing, we also assume that the demand for stumpage is perfectly elastic between $U_k$ and $L_k$ (see below). We define

$X_{ij}$ = the number of acres in compartment $i$ to manage under management alternative $j$

$V_{ij}$ = the harvest volume per acre removed from compartment $i$ if managed under management alternative $j$

$i$ = the compartment index where $i = 1, 2, \ldots m$

$j$ = the management alternatives index where $j = 1, 2, \ldots n$

$k$ = the planning period index where $k = 1, 2, \ldots t$

$C_{ij}$ = net present value ($NPV$) per acre if compartment $i$ is managed according to management alternative $j$

$U_k$ = the upper bound on the desired harvest volume in planning period $k$

$L_k$ = the lower bound on the desired harvest volume in planning period $k$

$A_i$ = the maximum acreage in compartment $i$ available for management

We then have

$$\text{Max } NPV = \sum_i \sum_j C_{ij} \cdot X_{ij}$$

subject to

$$\sum_i \sum_j V_{ij} \cdot X_{ij} \leq U_k \qquad \text{for all } k = 1, 2, \ldots t$$

$$\sum_i \sum_j V_{ij} \cdot X_{ij} \geq L_k \qquad \text{for all } k = 1, 2, \ldots t$$

$$\sum_j X_{ij} \leq A_i \qquad \text{for all } i = 1, 2, \ldots m$$

Under this formulation, $X_{ij}$ is treated as a continuous decision variable implying that a compartment can be managed under more than one alternative. This further implies a management strategy for a compartment that involves different cutting cycles and different dates of first entry. However, as long as all of the above cycles or periods are equal multiples of each other, the management strategy presents no serious scheduling problem. The real problem lies in the fact that if a stand is managed under two or more management alternatives, no guidance is given for locating the portion of the stand to be managed under each alternative.

As an alternative to the above formulation, we may wish to treat the whole compartment using one management alternative. To accomplish this, we redefine some of our variables. In this case, let

$X_{ij}$ = the proportion of compartment $i$ managed under management alternative $j$

$C_{ij}$ = the total net present value from compartment $i$ if managed under management alternative $j$

$V_{ij}$ = the total harvest volume from compartment $i$ if managed under management alternative $j$

We also require that $X_{ij}$ takes on the value of 0 or 1.

Generally, the above integer programing problem will be more difficult to solve computationally than the linear programing formulation previously presented. Thus, if an integer solution is desired, a common definition of management alternatives probably would be required to reduce the computational load.

The linear and integer programing problems presented above have been based on the premise that the compartment is the basic unit of management and the stand the operational unit for which a specific silvicultural treatment is specified. Thus, both formulations restrict entry into stands in a given compartment. Since the cutting cycles for all stands in a given compartment are equal multiples of each other, one or more stands are treated during each planning period.

As an alternative, we may do away with compartment boundaries entirely and schedule individual stands. In this case, the maximum number of management alternatives to consider is $\sum_{i=1}^{c} a \cdot s_i$, where $a$, $c$, and $s_i$ are as previously defined.

Under this approach, a stand could still be managed under two or more management alternatives. This can be avoided if an integer programing formulation is adopted. However, as mentioned earlier, the computational difficulty associated with solving this type of problem mounts rapidly as management alternatives increase in number.

Techniques for scheduling treatments for uneven-aged stands do not differ markedly from those used for even-aged management. Further, it makes no difference if even-aged stands are intermingled with uneven-aged stands. Thus, we believe that with few exceptions, uneven-aged management systems can be developed for large forest properties. However, actual case studies of this approach are not available in the literature.



# SUMMARY

The use of uneven-aged forest management has been limited in this country. One reason for this might be the belief that the practice of uneven-aged management is more of an art than a science. As a result, historically, few tools have been developed to aid the manager interested in applying uneven-aged management. However, recent Congressional and administrative decisions, along with increased public concern and involvement in forest management decisionmaking, are forcing uneven-aged management to be reevaluated as an alternative to current practices. With increased interest has come initial development of tools that can help the manager answer some pressing questions about uneven-aged management. Some aspects of uneven-aged management may remain an art but evidence is growing that more science can be introduced into it than previously was thought.

# PUBLICATIONS CITED


Adams, Darius M.
1974. Derivation of optimal management guides: a survey of analytical approaches. *In* Forest modeling and inventory--selected papers from 1973 and 1974 meetings of midwest mensurationists, p. 1-9 Dep. For., Sch. Nat. Resour., Coll. Agric. and Life Sci., Univ. Wis., Madison.

Adams, Darius M.
1976. A note on the interdependence of stand structure and best stocking in a selection forest. For. Sci. 22:180-184

Adams, Darius M., and Alan R. Ek.
1974. Optimizing the management of uneven-aged forest stands. Can. J. For. Res. 4:274-287.

Adams, Darius M., and Alan R. Ek.
1975. Derivation of optimal management guides for individual stands. *In* Proc. SAF workshop on systems analysis and forest resource management in Athens, Georgia., p. 132-147.

Alexander, Robert R., and Carleton B. Edminster.
1977a. Regulation and control of cut under uneven-aged management. USDA For. Serv. Res. Pap. RM-182, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Alexander, Robert R., and Carleton B. Edminster.
1977b. Uneven-aged management of old growth spruce-fir forests: cutting methods and stand structure goals for the initial entry. USDA For. Serv. Res. Pap. RM-186, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Davis, Kenneth P.
1966. Forest management: regulation and valuation. 519 p. 2nd ed. McGraw-Hill Book Co., New York.

Duerr, William A., and W. E. Bond.
1952. Optimum stocking of a selection forest. J. For. 50:12-16.

Ek, Alan R.
1974. Nonlinear models for stand table projection in northern hardwood stands. Can. J. For. Res. 4:23-27.

Ek, Alan. R., and Robert A. Monserud.
1974a. FOREST: a computer model for simulating the growth and reproduction of mixed species forest stands. Res. Rep. A2635. Sch. Nat. Resour., Coll. Agric. and Life Sci., Univ. Wis., Madison.

Ek, Alan R., and Robert A. Monserud.
1974b. Trials with program FOREST: growth and reproduction simulation for mixed species even- or uneven-aged forest stands. *In* Growth models for tree and stand simulation, p. 56-73, Fries (Ed.), Dep. For Yield Res., Royal Coll. For., Stockholm, Res. Note 30.

Hough, A. F.
1954. The control method of forest management in an age of aerial photography. J. For. 52:568-574.

Knuchel, Hermann.
1953. Planning and control in the managed forest. 360 p. Translated Mark L. Anderson. Oliver and Boyd, London.

Leak, William B.
1964. An expression of diameter distribution for unbalanced, uneven-aged stands and forests. For. Sci. 10:39-50.

Leak, William B., and Stanley M. Filip.
1977. Thirty-eight years of group selection in New England northern hardwoods. J. For. 75:641-643.

Loucks Daniel P.
1964. The development of an optimal program for sustained-yield management. J. For. 62:485-490.

Matthews, Donald M.
1930. Management plans for all age forests. J. For. 28:[057-]069.





Meyer, H. A.
1943. Management without rotation. J. For. 41:126-132.

Meyer, H. A.
1952. Structure, growth and drain in balanced uneven-aged forest. J. For. 50:85-92.

Meyer, H. Arthur, Arthur B. Recknagel, Donald D. Stevenson, and Ronald A. Bartoo.
1961 Forest management. 2nd ed. 282 p. The Ronald Press Co., New York.

Moser, J. W., Jr.
1972. Dynamics of an uneven-aged forest stand. For. Sci. 18:184-191.

Moser, John W., Jr.
1974. A system of equations for the components of forest growth. *In* Growth models for tree and stand simulation, p. 260-287, Fries (Ed.) Dep. For. Yield Res., Royal Coll. For., Stockholm. Res. Note 30, 379 p.

Moser, John W., Jr.
1976. Specification of density for the inverse J-shaped diameter distribution. For. Sci. 22:177-180.

Munro, Donald D.
1974. Forest growth models--a prognosis. *In* Growth models for tree and stand simulation,. p. 7-21. Fries (Ed.), Dep. For. Yield Res., Royal Coll. For., Stockholm. Res. Note 30.

Navon, Daniel I.
1975. Timber RAM User's Manual Part II: Forester's Guide. USDA For. Serv. Pac. Southwest For. and Range Exp. Stn., Berkeley, Calif.

Norman, E. L., and J. W. Curlin.
1968. A linear programming model for forest production control. Oak Ridge Natl. Lab. Dep. 4349.

Reynolds, R. R.
1954. Growing stock in the all-aged forest. J. For. 52:744-747.

Smith, David Martyn.
1962. The practice of silviculture. 578 p. John Wiley & Sons, Inc., New York.

Stage, Albert R.
1973. Prognosis model for stand development. USDA For. Serv. Res. Pap. INT-137, 32 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Steering Committee for Indian Reservation Forests.
1977. Making dollars and sense out of forestry. Proc. National Indian Timber Sym., February 23-25, Seattle, Wash.

U.S. Department of Agriculture, Forest Service.
1973. Silvicultural systems for the major forest types of the United States. USDA Agric. Handb. 445.

U.S. Department of Agriculture, Forest Service.
1975. Uneven-aged silviculture and management in the Eastern United States. Proc. in-Service workshop, July 15-17, Morgantown, W. Va.

U.S. Department of Agriculture, Forest Service.
1976. Uneven-aged silviculture and management in the Western United States. Proc. in-Service workshop, Oct. 19-21, Redding, Calif.

Walker, Nat.
1956. Growing stock volumes in unmanaged and managed forests. J. For. 54:378-383.

Ware, G. D., and J. L. Clutter.
1971. A mathematical programing system for the management of industrial forests. For. Sci. 17:428-445.

Hann, David W., and B. Bruce Bare.
1979. Uneven-aged forest management: state of the art (or science?). USDA For. Serv. Gen. Tech. Rep. INT-50, 18 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Examines some important historical factors that have caused widespread preference of the even-aged management system over the uneven-aged. Major decisions facing forest managers interested in applying unevenaged management are defined and a review is made of techniques traditionally used, or recently proposed, for use in making these decisions. Finally, problem areas needing further research and development are identified.

KEYWORDS: uneven-aged, even-aged, forest management, silviculture, management decisions, stand simulation, mathematical programing, optimization, compartment scheduling.

Hann, David W., and B. Bruce Bare.
1979. Uneven-aged forest management: state of the art (or science?). USDA For. Serv. Gen. Tech. Rep. INT-50, 18 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Examines some important historical factors that have caused widespread preference of the even-aged management system over the uneven-aged. Major decisions facing forest managers interested in applying unevenaged management are defined and a review is made of techniques traditionally used, or recently proposed, for use in making these decisions. Finally, problem areas needing further research and development are identified.

KEYWORDS: uneven-aged, even-aged, forest management, silviculture, management decisions, stand simulation, mathematical programing, optimization, compartment scheduling.